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Breaking New Ground? Taupo Volcanic Zone Geothermal Earthworm Surveys

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ABSTRACT

Earthworms were investigated as model soil organisms in low-temperature thermophilic zonation. Test site was adjacent to Paerata Rd. features of Mokai geothermal area. Dead worms were stranded beside an acid pool where Staphylinid beetles flourished, and fauna were excluded from inhospitable soil in gradients ranging 10-23°C with pH 7.3-4.5. Transect data indicated slight increase in abundance as topsoils cooled plus a significant positive correlation with rising pH partly attributed to self-regulation by the earthworms. A healthy paddock population of 7.2 million worms ha^{-2} (~1.6 t ha^{-2}) mainly comprised ubiquitous *Aporrectodea caliginosa* (Savigny, 1826) species-complex.

Incidental collecting at Wairakei-Taupo geothermal grounds and volcanic scoria mounds in Auckland unearthed *Anisochaeta macleayi* (Fletcher, 1889) and *Anisochaeta* spp. novae – these the first Australian species confirmed from New Zealand. New Australasian records are of acid-tolerant lumbricid *Dendrobaena attemsi* (Michaelsen, 1903) (from Mihi-Reporoa and Mt Wellington) and *Murchiona miniscula muldali* (Omodeo, 1956) from the Domain.

A dozen species were identified, five records new to science, none being endemics. These preliminary surveys demonstrate want of basic knowledge of fundamentals of native and alien life underground. Methods to rectify the neglect of subterranean soil fauna are proposed and their consideration in future geothermal environmental monitoring survey is promoted.

Keywords: Eco-taxonomy; soil fauna, transect, Oligochaeta : Annelida, biodiversity.

CONTENTS

INTRODUCTION

Primary aim of the project initially was to investigate diversity and abundance of organisms along a gradient of geothermally heated soil ranging from hot to cold. The thesis was that temperature and associated pH alterations, sometimes to as low as pH 1-2, would affect distributions with only well adapted soil fauna surviving. Because of their general abundance and intimate association with the soil, earthworms were chosen as model taxa. Similar studies considering geothermal influences on soil-dwelling organism are not known to have been conducted in New Zealand (NZ) nor elsewhere.

Waikato Regional Council (WRC, formerly 'Environment Waikato') recommends (unspecified) earthworms as indicators of "*soil quality*" while noting that this is satisfactory in just about 15% of the region's productive soils for their current land use in 2010, the remaining 85% of soils were "*Of concern*" (waikatoregion.govt.nz/Environmental-information/Environmental-indicators/Land-and-soil/Soil/land-6-key-points/ Oct., 2011).

Furthermore, earthworms are not only recognized as monitors and mediators of healthy soils, particular species are also cited as possible bioremediation agents, utilizing their natural activity characteristics and distributions, in soils contaminated by heavy metals, endocrine disruptors, pesticides, hydrocarbons, or radioactive radionuclides (Lee, 1985; Sims & Gerard, 1999). Globally, around 10,000 Oligochaeta worms have been named, perhaps not yet half those existing, and just ~220 are presently known from New Zealand from totals anticipated to be five or six times this large (Blakemore, 2010a, b).

Background to study

Waikato Regional Council's Regional Plan: Land and Soil Module (WRC, 2011) makes no particular reference to soil fauna, but as host to NZ's most abundant and diverse geothermal area in the Taupo Volcanic Zone (TVZ) it is mandated to monitor and preserve the environmental aspects. Geothermally active ecosystems are relatively concentrated here, as elsewhere, representing just 1000 ha (10 km^2 or ca. 0.00004%) of New Zealand's land area (Anon. 2004 and K. Luketina pers. com.) making them rare events that may be expected to have highly specialized, if not locally endemic, biota.

In an Environmental Impact Survey (EIS), Burns (2007) states: "*Species that occupy geothermal areas are tolerant of combinations of high temperatures and stressful environmental chemistry. Because they tolerate these extreme conditions, there is scientific interest in these organisms and they often have unusual and potentially valuable properties.*"

Thermophiles are organisms surviving at relatively high temperatures of 45-80°C, whereas extremophiles inhabit physically or geochemically harsh habitats, such as low pH acid waters, both terms mostly applied to microbes. Most EISs, however, concentrate on vegetation, birds, reptiles, and perhaps terrestrial Arthropoda, affording most other invertebrates cursory note other than for limnic/riparian/benthic components using protocols such as those developed by the 'New Zealand {Aquatic} Macroinvertebrate Working Group'. Most reports overlook soil fauna completely (e.g. Hutcheson, 1992, 1998; Duggan *et al*., 2007; Boothroyd, 2009).

In a thorough review paper of available information on geothermally influenced terrestrial (surface only, the subterranean link missed) and aquatic ecosystems of the TVZ, Boothroyd (2009) noted that such environments are "*characterized by steep soil temperature gradients, exposure to steam, have highly mineralized soils and waters, and extreme pH; other high-stress environments include those with shallow infertile soils.*" Regarding terrestrial invertebrates, Boothoyd (2009) focused mainly on insect such as Diptera and Coleoptera (flies and beetles) having tolerances in waters up to 55°C, while 'worms' were noted only in his Table 3 of aquatic macroinvertebrates (viz. predatory Platyhelminthes flatworms, small microdrile Oligochaeta and a few Hirudinea leeches).

Nevertheless, the examples that Boothroyd (2009) cited (also from Boothroyd & Browne, 2006) are when foraging taxa (e.g. Lauxianiidae flies and Formicidae ants) raided carrion. Specifics given were from Iceland where Elmarsdottir *et al*. (2003) found the number of spider and insect species to decrease and become habitat restricted as the temperature increased, as would reasonably be expected.

There are no known reports of earthworms under geothermal system soils in New Zealand (Dr Bruce Brown, UA, pers. comm. 14th Oct. 2011). Perhaps the most pertinent studies were nearly 60 years ago when Lee (1953: 49) noted temperature tolerance of the small (~23mm) endemic *Acanthodrilus kermadecensis* Lee, 1953 collected from steaming soil, almost too hot to handle (perhaps 50-60°C?), at the mouth of a fumarole in the main crater on subtropical Raoul Island, Kermadecs.

Recorded nearby was exotic *Eisenia fetida* (Savigny, 1928) that dominated forest litters on the island. That this species was reported at a hot spring in Iceland by Backlund (1949) was overlooked by Elmarsdottir *et al*. (2003).

It is noteworthy that *Eisenia fetida* – the "*tiger worm*" universally used in vermicomposting around the globe – is the most common introduced species in the Himalayas, is found on or under snow in Scandinavia and on subarctic Spitsbergen yet has experimental temperatures ranging from -2 to +40°C (Lee, 1985: tab. 2). Such wide tolerance appears exceptional, but this haemerobiont (associated with human activity) of northern Holarctic origin may be expected to tolerate both exothermic compost and cold ambient temperatures. Gates (1967) reports it as one of desert States fauna in the USA along with a few other exotic European lumbricids and Asiatic megascolecids, some from Hot Sulphur Springs (maybe place name rather than actual source).

Regarding distributions of earthworms in TVZ, Lee (1959: 439) surveyed soils from geologically recent volcanic activity examining those formed of pumiceous material from Mt Tarawera and mud from Lake Rotomahana ejected during the 1886 eruption. In general he found natives in the muds but excluded from the coarser and abrasive ash deposits. Further descriptions by Lee (1959) and Blakemore (2010b) are of native Megascolecidae *s stricto* well south of a putative exclusive "*Taupo-line*".

Amongst natives previously described from Lake Taupo-Rotorua region are: Acanthodrilidae *Rhododrilus aduncocystis* Lee, 1959 and *R. similis* Benham, 1906 along the Waikato River, and Megascolecidae *Celeriella antarctica* (Baird, 1871) in the form of its synonym *Diporochaeta shakespeari* Benham, 1905 at least, found by Lee (1952) in western coastal ranges of the Waikato and Taranaki districts. *Megascolides fuscus* Lee, 1952 is from "*topsoil and subsoil in Taupo sandy silt in areas of native rain forest and exotic forest (Pinus spp.) in the Rotorua district*" along with *Diporochaeta obtusa* Lee, 1952 that is particularly widespread elsewhere. *Notoscolex sapidus* (Benham, 1904) was collected from Ruatahuna between Rotorua and Lake Waikaremoana; and *N. suteri* (Benham, 1904) range extends from Auckland to Rotorua-Taupo where its common habitat is under rotten logs (Lee, 1952, 1959). Previously described exotics (Lee, 1959, Martin, 1977; Blakemore, 2010a, b) include *Dendrodrilus rubidus* sub-spp and several other Lumbricidae of probable direct or indirect European origin.

Study Site

A potentially suitable survey location was within the Mokai geothermal area that displays only a few superficial manifestations as steaming ground or hot springs yet contains some of the hottest geothermal wells in New Zealand ranging 300-330°C. Two power plants (45 and 21 MW) were installed to 2005 by Tuaropaki Trust and operated under contract by Mighty River Power (25% ownership). The Paerata Road site is recognized for its heated ground habitat, mud geyser and mud pools that are fenced within part of pasture farmland (cattle, sheep and alpacas) near the Dried Milk Factory and above the 12 ha glasshouse facility that both use binary conversion of geothermal energy to heat the plants and to dry the milk (Geothermal PGCert. 603 field trip notes, 15th Sept., 2011).

WRC is required to collect environmental information to comply with its obligations under Section 32 of the Resource Management Act 1991, thus the Paerata Rd. site is included in Annual Monitoring Reports (e.g. Lynne, 2009; Newson, 2010). Paerata Rd. feature "P4" corresponds closely to the area surveyed with its eight pools and small hot seeps with temperatures 24-45°C and pH range 2.3-4.6, near zero flow and calm ebullitions of murky grey-brown mud with black scum (Figure 1). Adjacent sites had hot seeps up to 77°C and a small gas discharge without visible liquid at 93°C.

Figure 1. Paerata Rd Feature "P4". Photo courtesy J. Newson (Newson, 2010: fig. 5-11).

The field site is mapped in relation to consents and according to WRP Geothermal Variation June, 2008 "*Draft Consent Order Attachment of Maps of Significant Geothermal Features*" (Doc #1130498 mapsgeothermalfeatures.pdf: 74) in Figs. 2a, 2b.

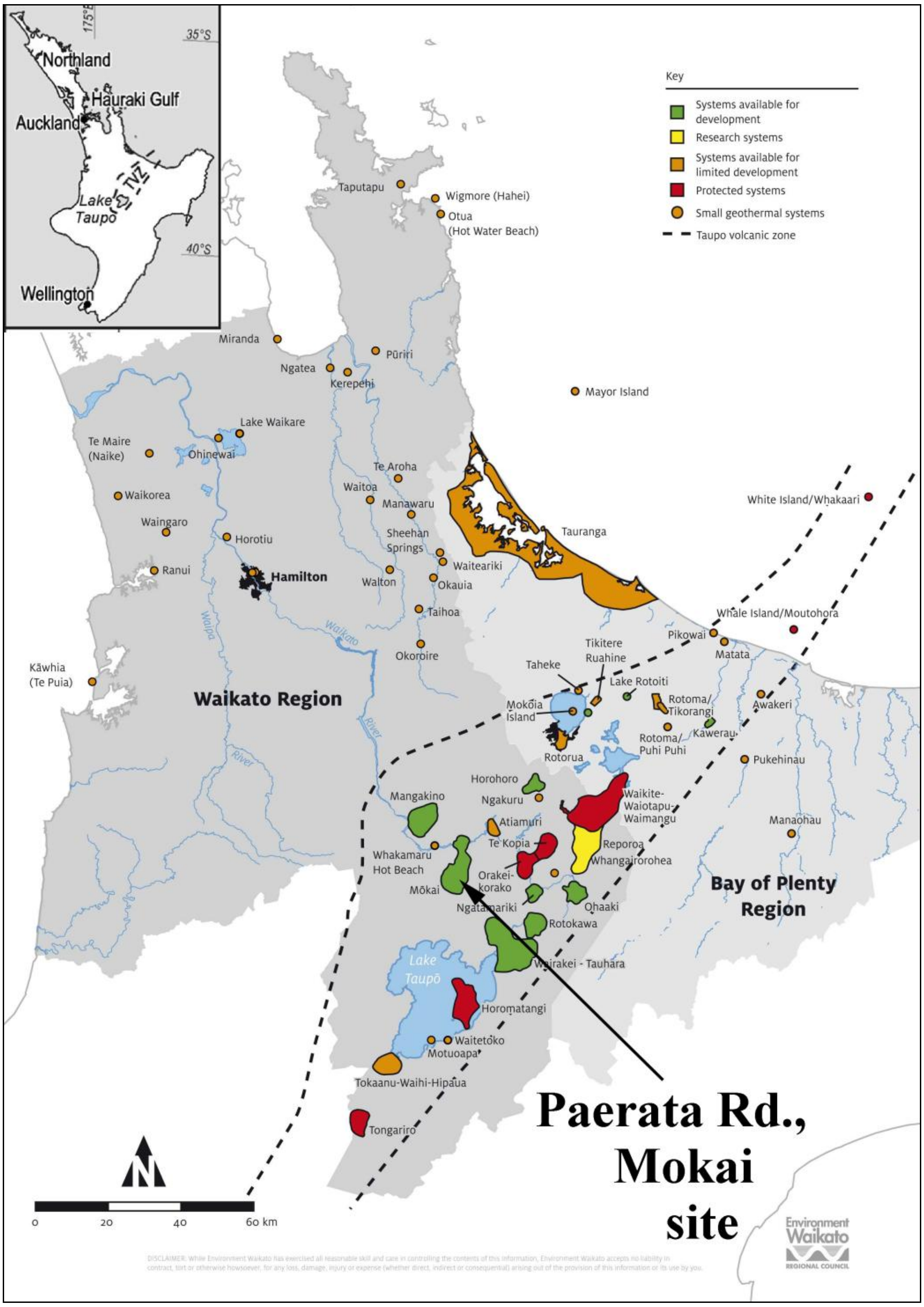

Figure 2a. Plan of Mokai Geothermal Field in TVZ (adapted courtesy WRC sources).

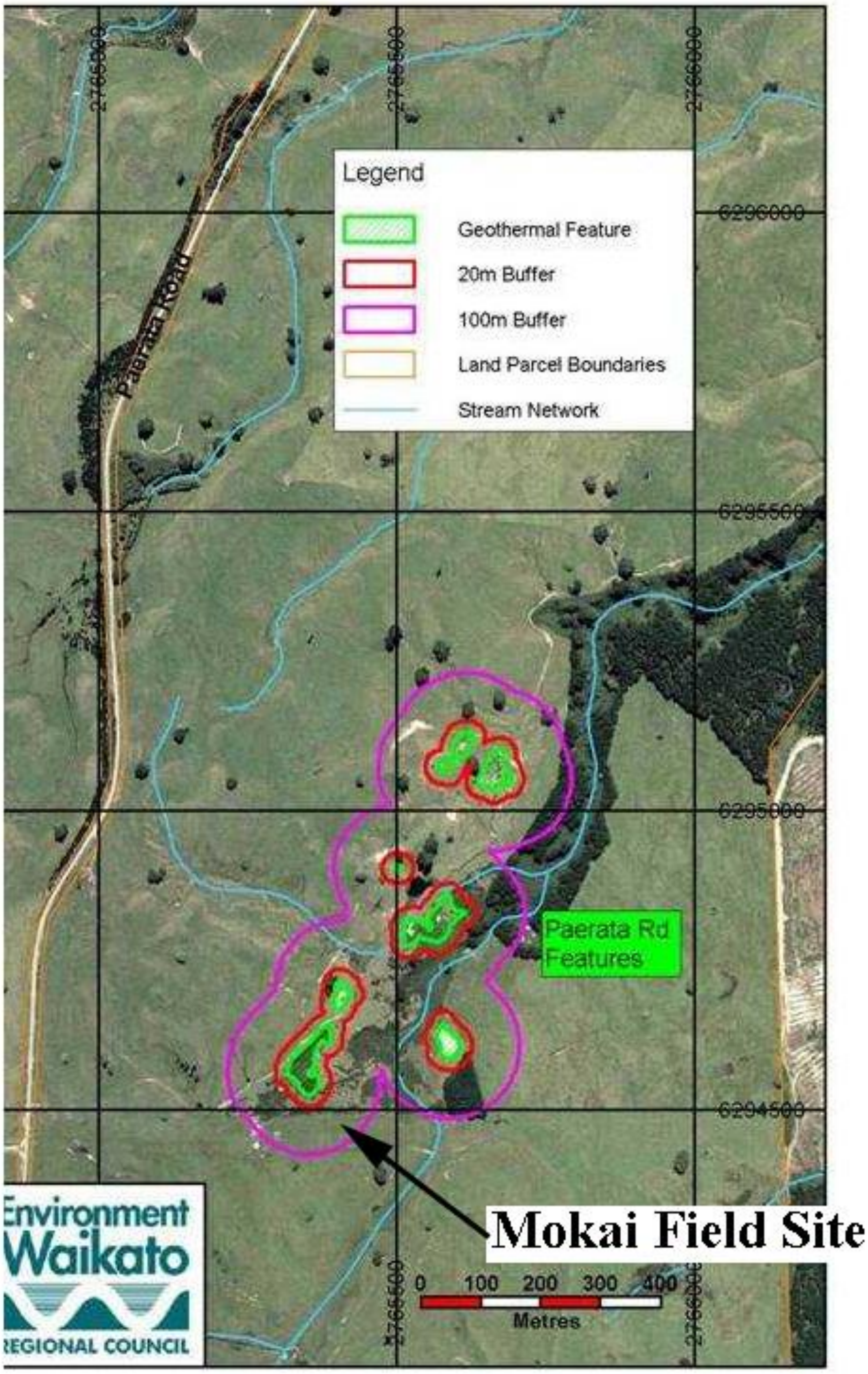

Figure 2b. Plan of Paerata Rd., Mokai site's geothermal features (courtesy WRC).

Preliminary environmental survey data are in a "*Plan for Pest Plant and Animal Control*" by Bycroft & Beadel (2006) where they state Paerata Rd.: "*Contains the best population of prostrate kanuka scrub and shrubland in the Mokai Geothermal*

Field. Prostrate kanuka is endemic to geothermal sites in New Zealand and is an 'At Risk' species listed as 'Range Restricted' in de Lange 2004." The only weeds/pests they identified were blackberry and rabbits. Bait traps noted on some fences, possibly for possums or Mustelid ferrets, stoats and weasels that include earthworms in their diets.

MATERIALS & METHODS

Qualitative collection was made at Mihi/Golden Springs near Taupo (11th Sept., 2011) and Wairakei Steamfield (13th Sept., 2011) during the field trips (Geothermal PGCert. 603). Volcanic scoria cones at Mt Wellington (14th Oct., 2011) and the Domain (27th Oct., 2011) in Auckland were briefly investigated as *ad hoc* opportunity presented itself.

Quantitative quadrat survey was conducted along transects at the Paerata Rd., Mokai site as located in introduction above and as shown in sketch plan below (Figure 3).

Field experiment was conducted by taking soil quadrats along three transects starting from geothermal manifestations and progressing into adjacent ca. 7 ha pasture paddock, southwards in each case, with distances measured by calibrated wheel. Soil and vegetation descriptions courtesy of Dr Bruce Willoughby (BW) are attached unaltered in an Appendix.

Soil fauna were represented by earthworm populations retrieved by digging 16 x 16 cm cores to the depth of 15-16 cm while noting that most activity was in the top 5+ cm rhizosphere or rootzone. Specimens were sorted from soil/roots by hand on plastic. Incidental scarab larvae were also collected but other macroivertebrates were sparse.

Field identifications were made, and representative samples were anaesthetized in dilute alcohol before being fixed and preserved in 80% EtOH and labeled for formal identification under low power binocular microscope. Specimens of particular interest are deposited with accession numbers prefixed AMNZ in the Auckland Museum (DNA analyses pending). Biomass estimates used domestic quality scales that were further rendered inaccurate by removal of representative samples plus mortality during overnight storage and transportation to Hamilton, yet data are presented for completeness.

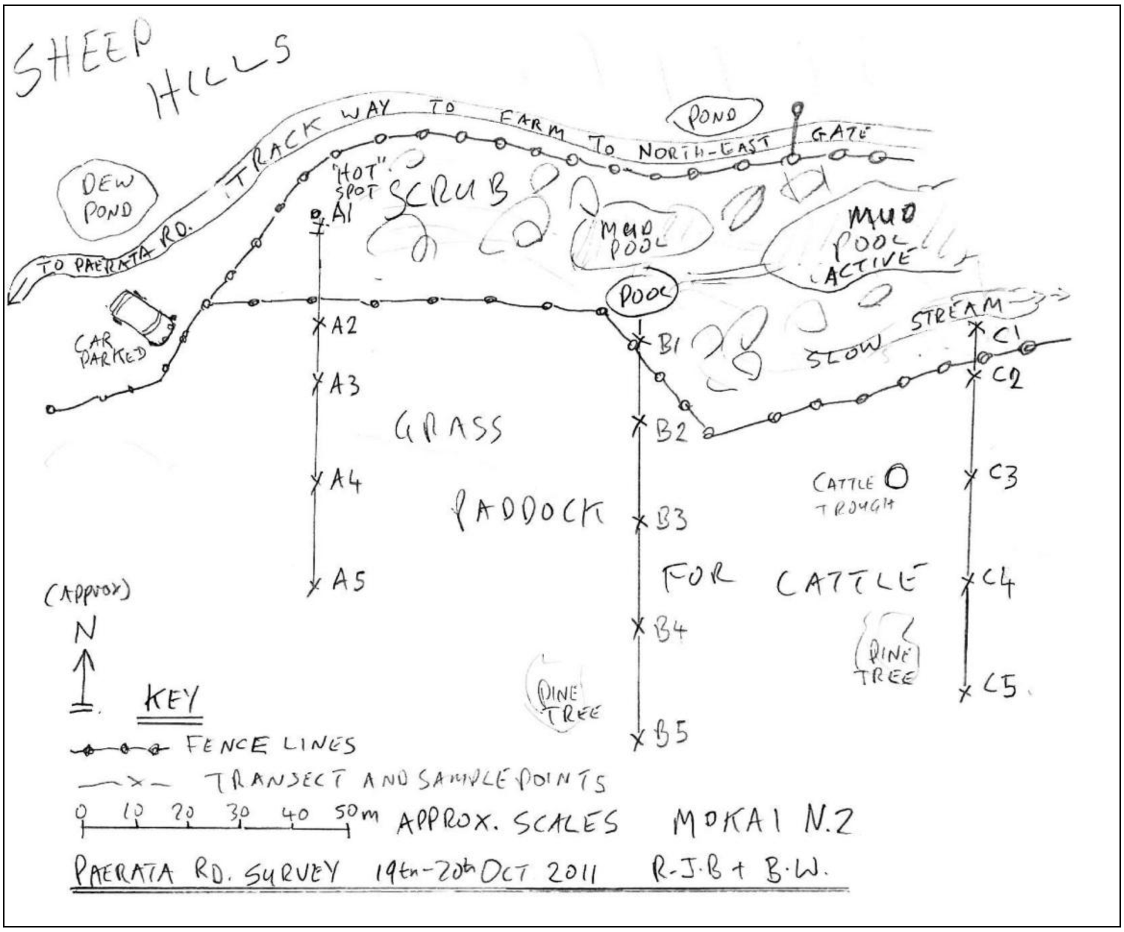

Figure 3. 'Mudmap' sketch of transect survey site and schedule at Paerata Rd., Mokai. (Note: trackway traverses more towards north-northeast than shown).

Sampling closer to active features was precluded due to WRC Occupational Health and Safety (OH & S) condition restriction to avoid a minimum 2m boundary.

Temperature and pH metering

Soil temperature and pH measurements used HANNA HI 98128 'pHep' (for its specifications, see: www.hannainst.com/usa/prods2.cfm) with automatic pH calibration, temperature compensation and accuracy of pH ±0.05; Temp. ±0.5°C (Figure 4). Terminals were rinsed between readings in bottled water.

Temperature readings were compared using laser spot and (10cm long prong) temperature probe of FLUKE 566 IR Thermometer (Figure 5).

Figure 4. HANNA meter. Figure 5. FLUKE meter.

Starting locations were fixed by GPS at post near feature for Transect A otherwise from nearest fence-line (for Transects B and C) as tabulated in Results.

<u>Statistics</u>

Population and geophysical data were subjected to a series of statistical analyses using one-way or multiple/factorial ANOVA (ANalysis Of VAriance) and Pearson product-moment correlation coefficients with Regression/Correlation charts (using online programs of VassarStats and MSExcel). The raw statistical results and their brief interpretational commentaries and charts are presented in Appendix I.

RESULTS

Table of Transect localities fixed by GPS (courtesy of BW) and collection conditions.

***Position**	**GPS Southing**	**GPS Easting**	**Altitude m amsl**	**Date/ Weather**
Upper Transect - A "Hot Patch"	38°30'.946	175°55'.545	517.0	20/10/2011 Fine
Mid Transect - B "Tepid Mud Pool"	38°30'.968	175°55'.617	508.9	19/10/2011 Rain
Lower Transect - C "Ebullient Stream"	38°30'.943	175°55'.705	507.8	20/10/2011 Fine

*[Cf. GPS data given by Newson (2010) (from Lynne, 2009) of E2765402.N6294657; and local maps with nearby TRIG points altitude at 447-499m].

[A remote weather station was situated beside the Mokai site track, but data logs for it were not located online to verify altitude nor to provide temperature/rainfall readings].

Subsurface measurements at 10 cm (depth of HANNA meter probe) are presented for each Transect with worm biometry. Data prefixed ‘Sample’ were taken from the grazed paddock subject to trampling and manuring by the ~30-head heifer dairy stock (cattle), whereas other samples were from inside of the feature fence-line.

Abbreviation used in the tables below are:

A. cal - *Aporrectodea caliginosa* (Savigny, 1826) paler morphs.

A. trap - *Aporrectodea* cf. *trapezoides* (Dugès, 1828) darker morphs.

L. rub - *Lumbricus rubellus* Hoffmeister, 1843, red colour, tanylobous.

O. cy - *Octolasion cyaneum* (Savigny, 1826), milky white, flaccid.

Lumbricids - mixtures of unidentified Lumbricidae spp, probably those above.

Table of Transect A data (from stunted grass 'Hot Patch') with fence at ca. 19 m.

Reference point	**Temp °C**	**pH**	**Worms**	**Mass g**	**Spp (field ID)**
Ambient air	19.0	-	-	-	-
Surface	24.0 (solar?)	-	-	-	-
A1 Hot Patch	13.10 (mean) @ 10cm	5.80 (mean) @ 10cm	5 to 15cm	1.0 g	A. cal.
A2 Sample 20m S	12.9	6.2	30	5.0g	A. trap mainly some A. cal
A3 Sample 30m S*	12.90 (mean)	7.3	37	?	A. trap mainly, some A. cal, L. rub rare
A4 Sample 50m S	11.1	6.1	11	3.0	A. trap mainly, some A. cal
A5 Sample 70m S	13.8	6.1	17	6.0	A. trap mainly, some A. cal, O. cy rare

*Sample collected day before on 19th Oct., 2011; plus two scarab larvae and a pupa.

Table of Transect B data (from Tepid Mud Pool with H_2S smell) fence at ca. 7 m.

Reference point	**Temp °C**	**pH**	**Worms**	**Spp (field ID)**
Tepid Mud Pool	18.8	2.9	-	-
Surface at edge	15.6 (rainy day)	?	Many dead on surface*	Lumbricids
B1 Soil 3m S	13.6 @ 10cm	4.8 @ 10cm	7 to 15cm	A. cal mainly, L. rub rare
B2 Sample 20m	16.7	5.0	1	A. trap, A. cal.
B3 Sample 40m	15.2	5.3	27	A. cal, A. trap. L. rub
B4 Sample 60m	13.4	5.7	17	A. cal mainly
B5 Sample 80m S	10.4	5.7	13	A. cal

*Many Staphylinidae burrows with few predacious larvae in occupancy in embankment.

Table of Transect C data (from bubbling Slow Stream with H_2S smell) fence at 9 m.

Reference point	**Temp °C**	**pH**	**Worms**	**Mass g**	**Spp (field ID)**
Slow Stream	15.1	6.3	-	-	-
Surface at edge	16-20	-	-	-	-
C1 Soil at 2m S	22.5 @ 10cm	4.5 @ 10cm	0 to 15cm	0	-
C2 Sample 10m S	15.0	5.7	9	1.0 g	A. cal mainly, L. rub, O. cy
C3 Sample 30m S	16.2	5.9	21	4.0g	A. cal mainly, O. cy rare
C4 Sample 50m S	15.3	6.5	13	5.0	A. cal mainly some A. trap
C5 Sample 70m S	17.4	6.7	19	4.0	A. cal mainly some A. trap*

*Scarab larva collected and sent to Christchurch specialist for identification by BW.

Species identified at Mokai were primarily *Aporrectodea caliginosa* species-complex; however two superficial Mokai morphs were recognized as "*A. caliginosa*" and "*A.* cf. *trapezoides*", as detailed in Discussion. Other earthworms recovered infrequently were *Lumbricus rubellus* that inhabits organic rich soil and manure, and *Octolasion cyaneum* a geophage (mineral soil diet) often implicated as a first colonizer in disturbed sites or as a pioneer species. Only indication of species differences were that "*A.* cf. *trapezoides*" was more prevalent and numerous in the upper paddock (Transect A), while "*A. caliginosa*" appeared dominant in the lower paddock (Transect C) where *O. cyaneum* was also slightly more frequent. [Sample specimen sketches are presented below as Figures 6-7]

Incidental Earthworm Survey Results

Eisenia fetida (Savigny, 1928) was confirmed as the species used in extensive vermicomposting windrows of greenhouse green waste from heated glasshouses adjacent to the Mokai Geothermal Plant (RJB pers. obs.) on the 603 field trip, 15th Sept., 2011.

Earthworms from Golden Springs, Mihi-Reporoa [data from Newson (2010: Tab. 3.2) for South Geothermal Pool on Motel grounds, E2798774.N6298395, water temperature 33°C, pH 7.4, flow ~40 l/s], were identified as: *Aporrectodea caliginosa* proper, *Dendrobaena attemsi* (Michaelsen, 1903) - a new record for New Zealand/Australasia of this European interloper (AMNZ 5258); *Dendrodrilus rubidus tenuis* (Eisen, 1874) (AMNZ 5259); and possibly *Octolasion cyaneum* (specimens not kept); plus *Anisochaeta 'mihi' sp. nov.* - this a newly recorded introduction as yet unnamed in its Australian homeland (AMNZ 5260-5261). [Specimen sketched below as Figure 8]

Earthworms found at Wairakei Geothermal Station near to well WK44/0 were: *Anisochaeta macleayi* (Fletcher, 1889) – the first confirmed record for NZ of an known Australian native species (see Blakemore & Elton, 1994; Blakemore, 2000a; 2008, 2010a) [(AMNZ 5262-5263) specimens sketched in Figure 9 cf. Figure 10 of *A. laingii*]; *Aporrectodea trapezoides* (AMNZ 5264), same as those found in Australia, Asia and Japan, but different in appearance to the Mokai morphs, plus a specimen of *Octolasion cyaneum* that was released.

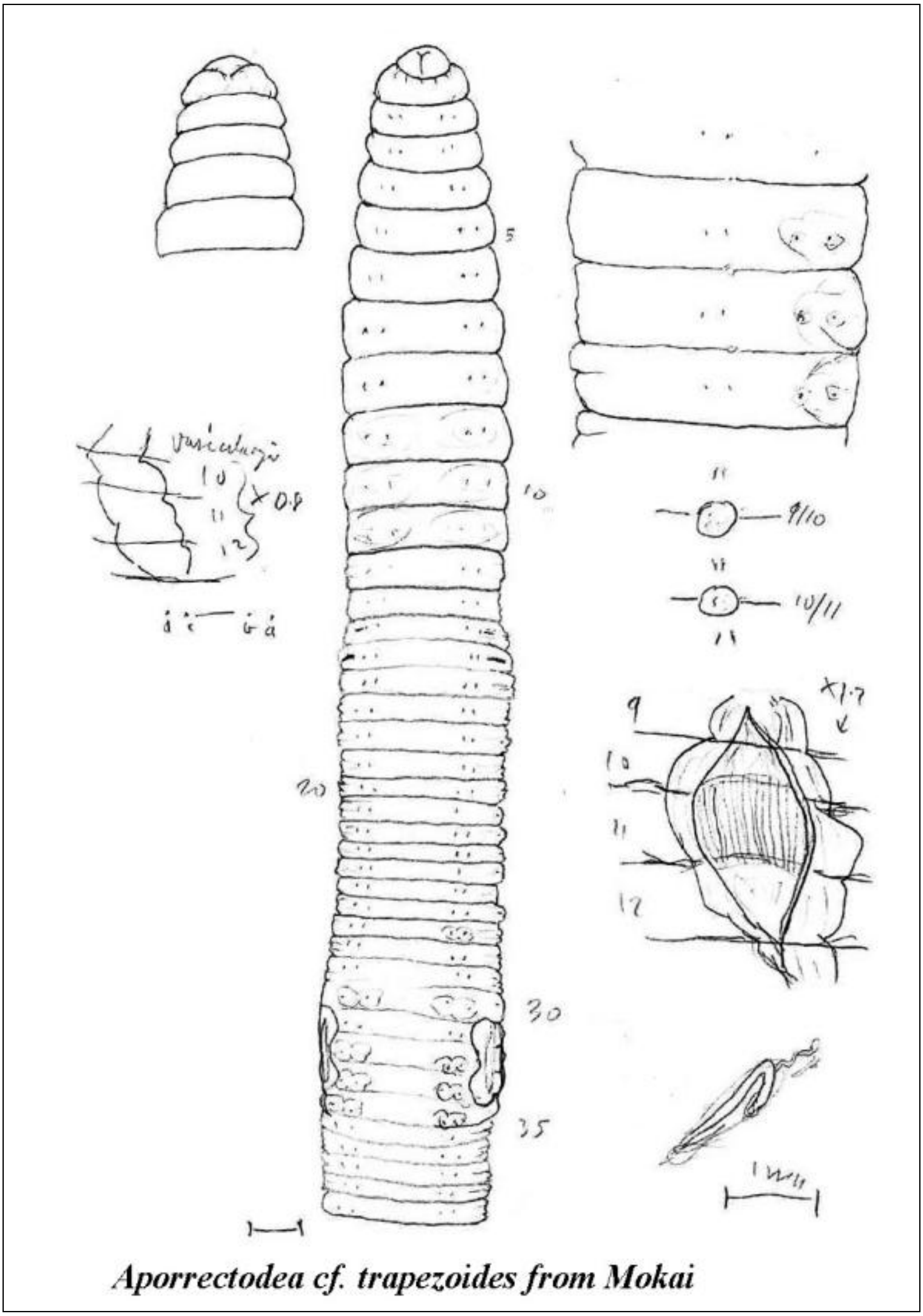

Figure 6. Sketch of Sample #1 ex quadrat A3, mainly dark forms identified in the field as "*A.* cf. *trapezoides*" (AMNZ 5273 DNA RJB01).

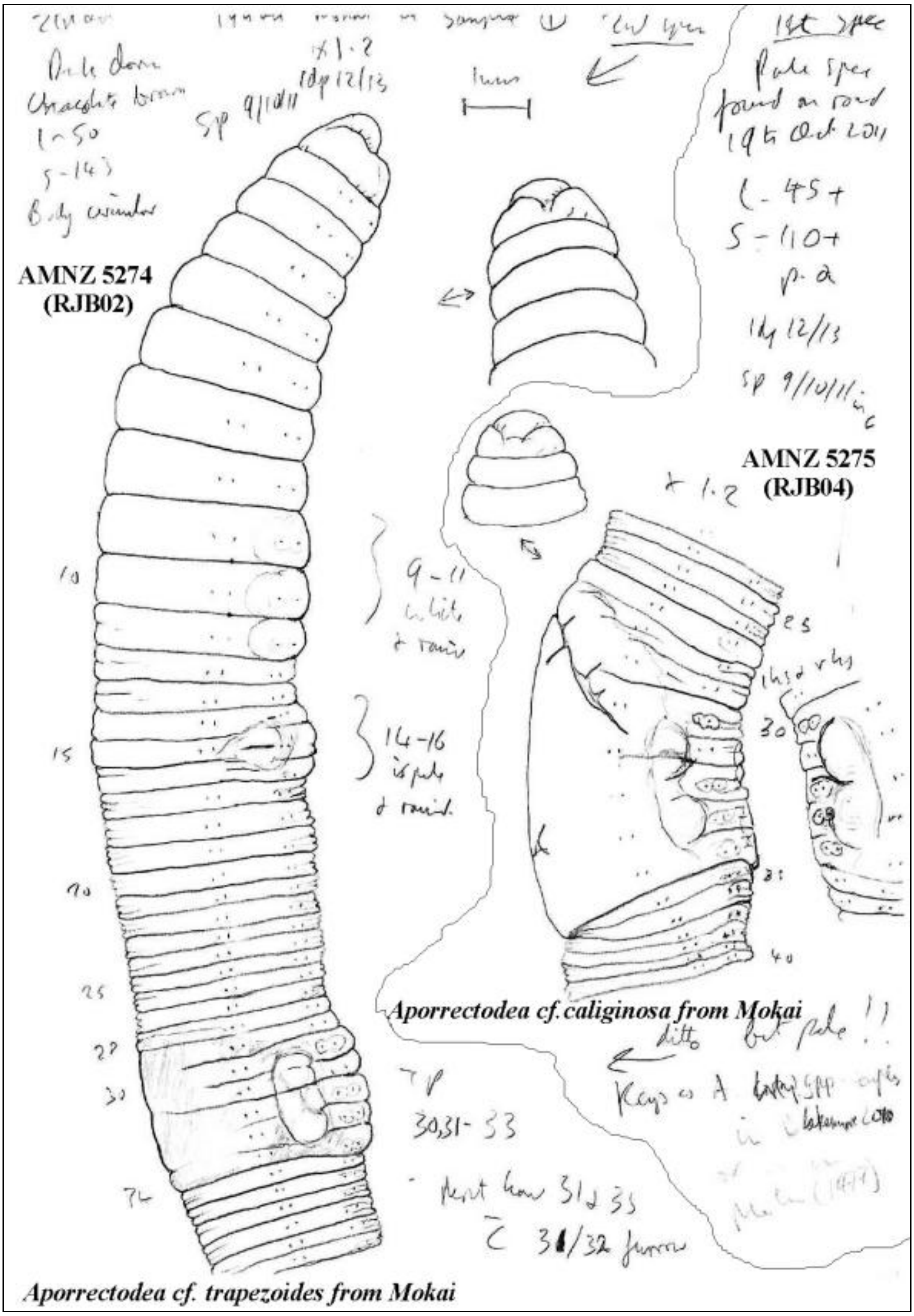

Figure 7. Sketch of specimen #2 (AMNZ 5274 DNA RJB02) and #3 (5276 RJB04).

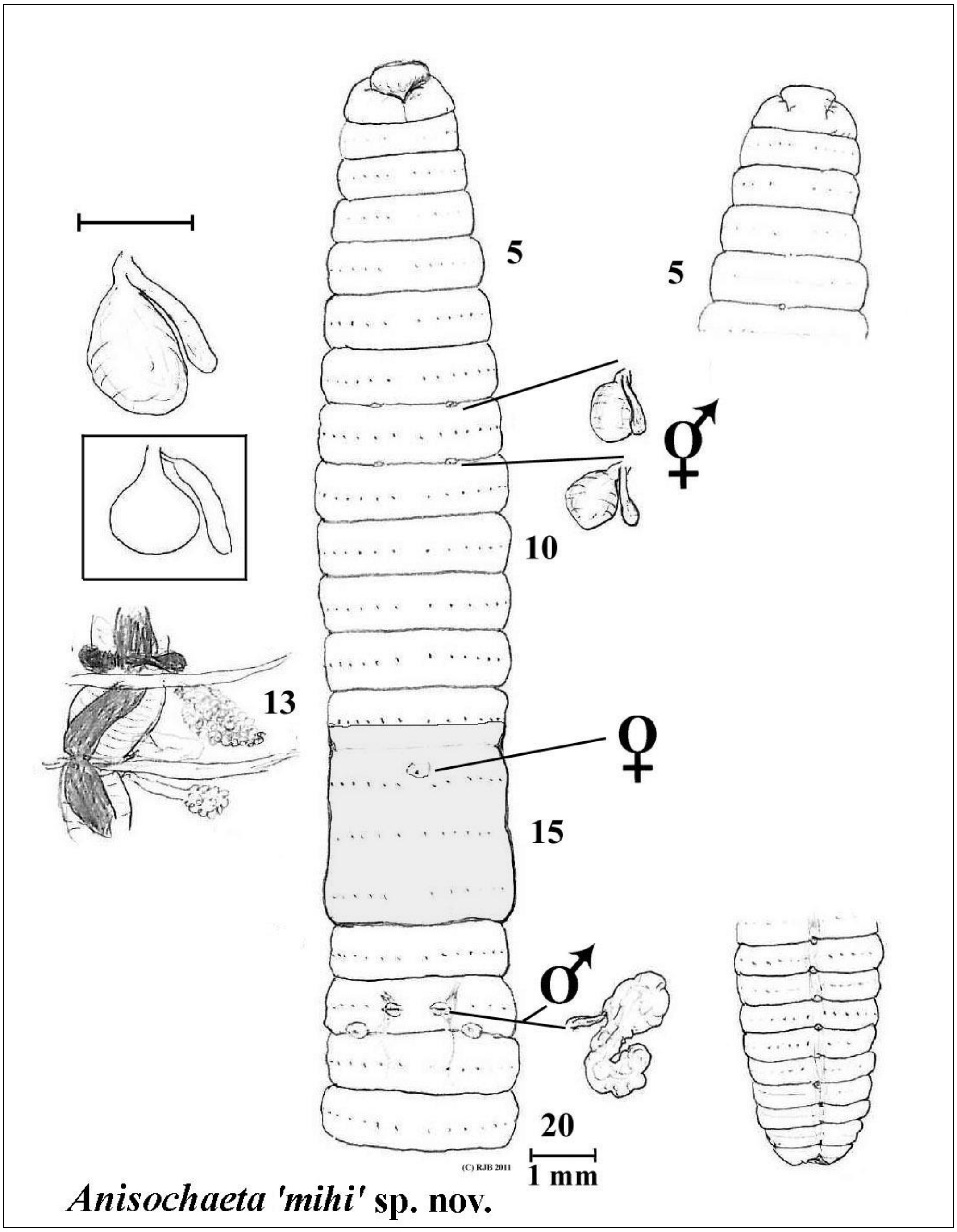

Figure 8. *Aporodrilus ‘mihi’* sp. nov. from Golden Springs, Mihi-Reporoa, NZ. Ventral view with dorsal view of prostomium, spermathecae, prostate and oesophageal gland in 13 *in situ*; plus tail end. [Boxed spermatheca (near enlargement of 8rhs) is of *Anisochaeta laingii* (Benham, 1903) from Lee, 1959: fig. 305 for comparison).

[**Please note: Name is provisional and is embargoed until formal publication**].

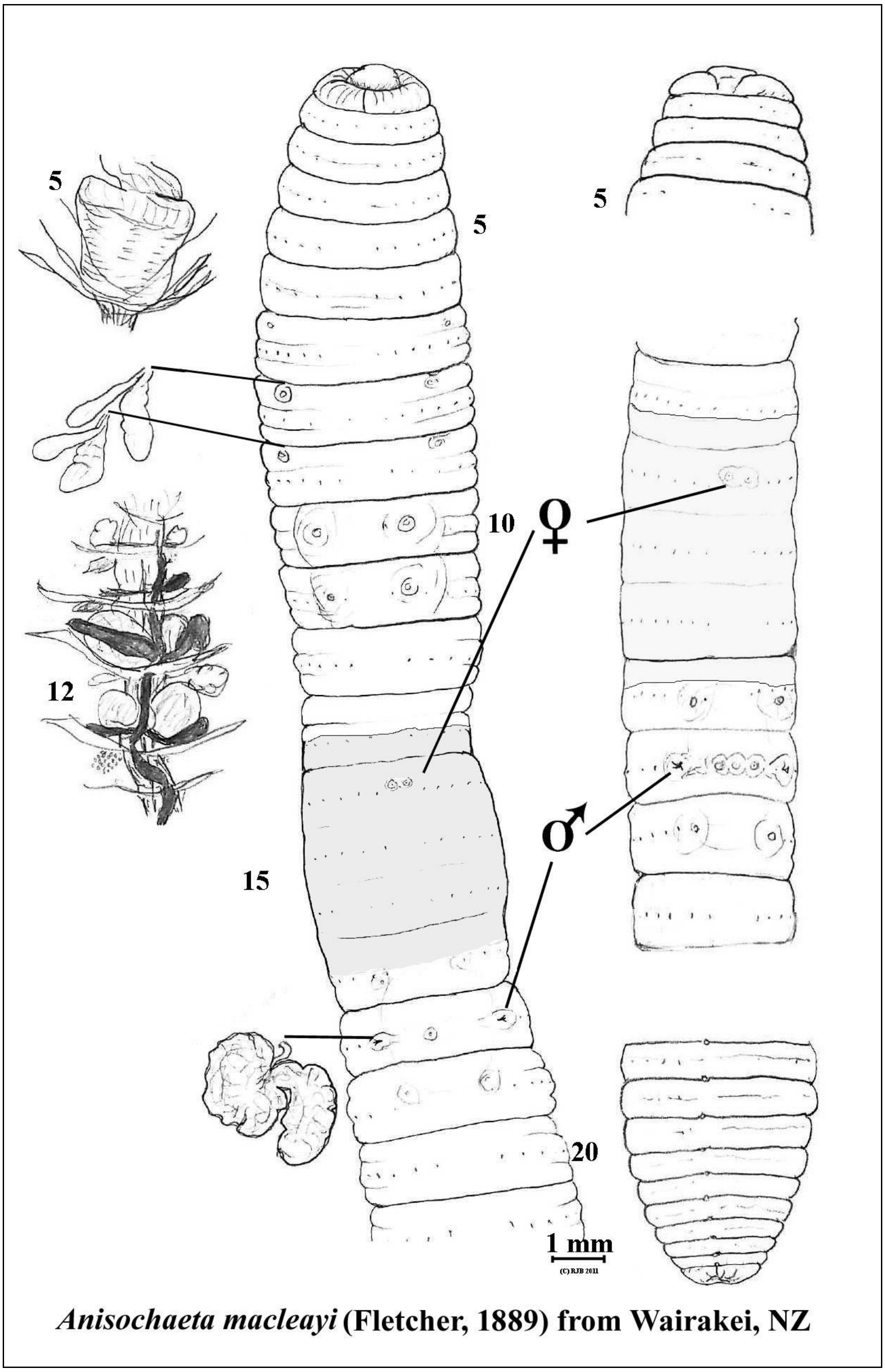

Figure 9. *Anisochaeta macleayi* (Fletcher, 1889), Wairakei Steamfield nr. well WK 44/0. Coll.: RJB, 13.IX.2011. Central specimen AMNZ 5262, rhs specimen AMNZ 5263.

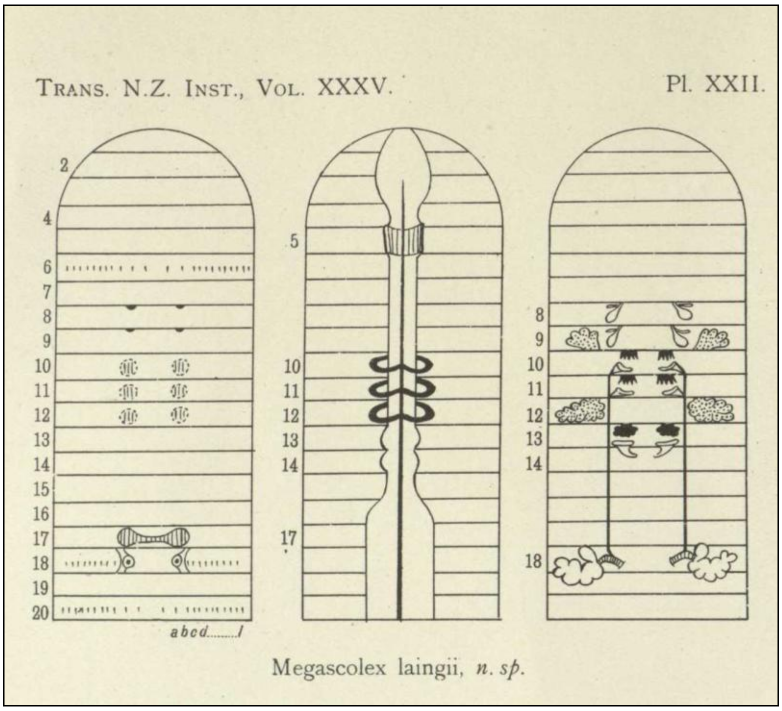

Figure 10. *Anisochaeta laingii* (Benham, 1903) from Norfolk Island, the only previous NZ *Anisochaeta*. Its markings in segments 10-12 and 17 differ but internal organization is somewhat similar to the Mihi worm. (Copy permission from Royal Society NZ by email, Oct., 2011).

Earthworms (AMNZ 5262-5268) collected at Mt Wellington in Auckland, a scoria cone given over to cattle pasture, were identified as: *Lumbricus terrestris*; *Aporrectodea caliginosa*; *A. tuberculata* (Eisen, 1874); *Lumbricus rubellus*; Octolasion *cyaneum*; *Anisochaeta sp.* [comparable to the Golden Springs worm and different again from *Anisochaeta laingii* (Benham, 1903) thus possibly a new species?], and *Dendrobaena attemsi* – this only the second collection of this worm after Golden Springs (Figure 11). These seven species, unearthed in less than an hour, show possible pasture assemblage diversity (rather than the two or three usually reported, e.g. by Lee, 1985). Plus at the Domain near the stream outlet that was Auckland's original water supply *en route* to the Museum on 27th October the *Murchiona muldali* (Omodeo, 1956) morph of *Murchiona minuscula* (Rosa, 1906) was found as yet another new record for New Zealand of an introduced European lumbricid (Figure 12). [Additionally, three new natives identified from material in the Auckland Museum's collection are also in process of description (Blakemore, in prep.)].

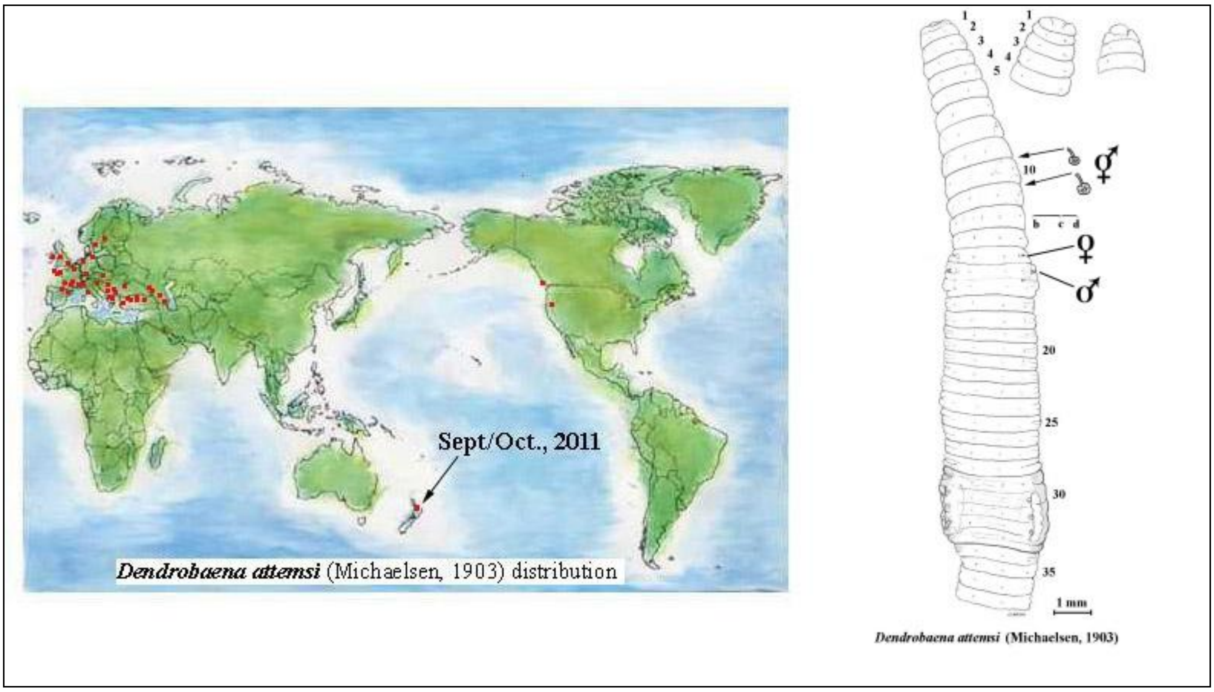

Figure 11. *Dendrobaena attemsi* (Michaelsen, 1903) distribution including “Golden Springs”, Taupo and Mt Wellington, Auckland, NZ; sketch of specimen (AMNZ 2569).

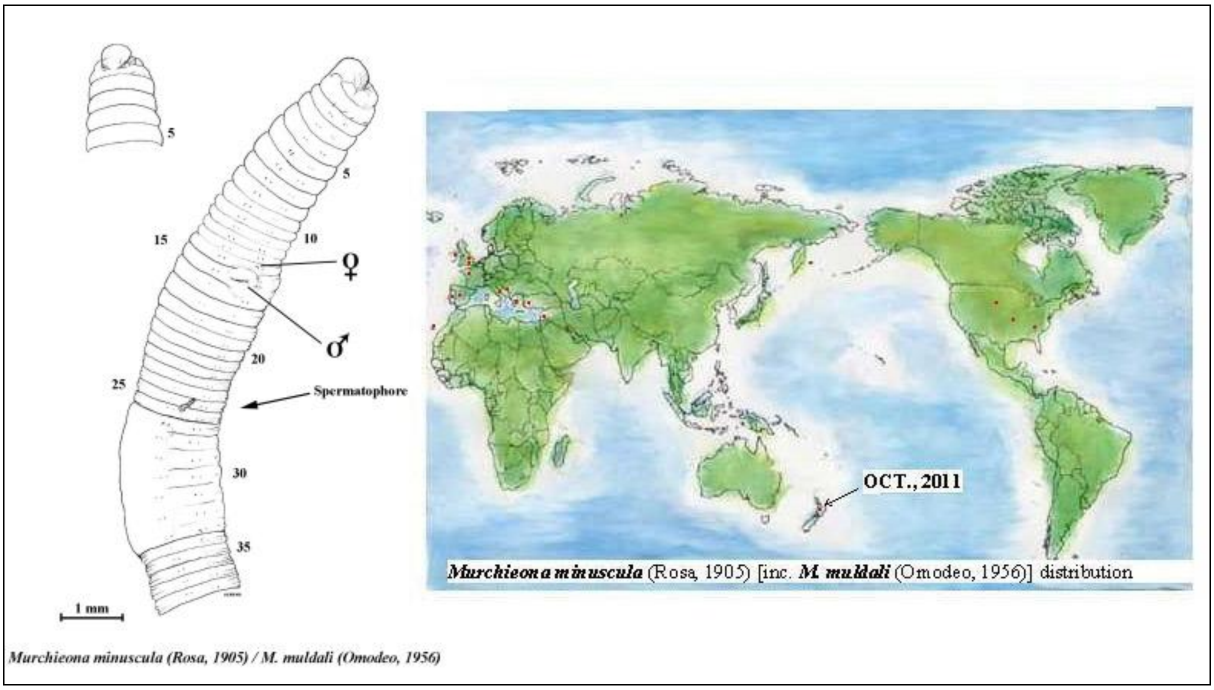

Figure 12. *Murchiona minuscula muldali* (Omodeo, 1956) distribution and sketch of NZ specimen (AMNZ 2579) collected RJB 27th Oct, 2011 from the Domain, Auckland.

DISCUSSION & CONCLUSIONS

The Mokai transects did not provide as clearly defined geothermal gradients as expected, this attributed to temperatures being insufficient and too irregular to impart significant influence radially. While Transect A appeared to be quite uniform, transect B was inconclusive (possibly due to rain effects) and although a more definite trend was seen for Transect C, its highest temperatures were at either end. However, combined data (Appendix I) showed definitively that earthworm abundance corresponded to physico-chemical conditions. The pH response was most defined, but is assumed to be partially self-induced by the activity of the worms as well as due partly to geothermal alterations as shown by slight correlation trend of soil temperature vs. pH.

Earthworm diversity was fairly uniform according to the methods employed. Neither thermophylic nor extremophilic species were categorized at the Mokai site although comprehensive qualitative collection was not attempted, temperatures were relatively cool and, where conditions were more severe and active, access was restricted. The only earthworms found were exotic introduced species that have generalist survival tolerances characteristic of widely-distributed cosmopolitan species (Lee, 1985; Blakemore, 2010a).

Soil Measurements Assumptions and Errors

Across all transects, the mean soil temperature @ 10 cm depth was 14.63°C ± s.e. 0.753 (n = 15) somewhat higher than would be expected in late Spring thus due partly to geothermal heating, and the pH was 5.82 ± s.e. 0.189 (n = 15) or slightly acidic overall.

Self-calibrating equipment may not have provided absolute temperatures nor pH readings, and the FLUKE 'gun' tended to give widely variable results (its probe taking a long time to stabilize in soil and its laser giving pin-point readings). The most consistently reproducible and reliable data was from the HANNA recorder, as used here. However, since the concern is relative differences, the exact values are not as essential.

Thompson (1965) reported on shallow temperature and soil sampling at Taupo and Hochstein & Bromley (2005) in areas of steaming ground at Wairakei (Karapiti) and Tauhara. The latter revealed thermal diffusivity of pumice soils averaged about 0.4E-6m^2/s and thermal conductivity varied between 0.4-1.4W/mK in response to

variation in the moisture content of 100-700kg/m^3 and due to atmospheric pressure and diurnal solar heating. Their raw logger data showed temperature at 10 cm depth at Karapiti averaged approximately 45°C with clear fluctuations, as would be assumed, according to rainfall, solar and diurnal variation. These temperatures are substantially higher than those in the Mokai soils that averaged just less than 15°C in the paddock at 10 cm depth, but may explain why the Transect B data collected in rain was lower (by about 2°C) than the average for either of Transect A or C taken in fine conditions.

Sustained effects on vegetation of elevated temperatures is revealed in thermal contouring that can detect shallow low-thermal reservoir prospects e.g. as at Whitford near Auckland by Boedihardi & Hochstein (1990). Relationship between soil temperature and heat flow (from Prof. M. Hochstein's lecture notes on heat loss for hot water systems in NZ, modified from "*Dawson, 1964: NZ J. Geol. Geoph. 7: 155-171*") are shown in the following Table (see also Hochstein & Bromley, 2005; Bromley *et al.*, 2011). As yet no temperature link is made with subsurface biota and soil fauna.

Table of relation between ground condition, soil temperature and heat flow

Grade	**Ground condition**	**Temp. °C**	**Depth**	**Heat flow (W/m^2)**
Super hot	Bare ground, audible vents	97	0-1.5	12600
A	Bare ground, steam	97	1.5-3	4200
B	Bare ground, clay	97	3-7	2100
C	Dead wood, algae*	97	7-13	840
D	Moss	97	13-24	420
E	Moss, lichen	80-85	15	250
F	Low vegetation (manuka)	60-80	15	125
G	Vegetation (manuka, broom)	40-60	15	42

*As dead plants can only come from living ones, these must indicate (recent) flux.

The upper feature of the Paerata Rd. site had a patch of moss and dead or quiescent grass (Transect A) which may be taken as between Grade D-E; and the low scrub (prostate kanuka/manuka) reported on site may indicate Grades F-G between the pools nearer Transects B and C.

As for the Mokai features, mud pools and calm pools are thermal discharge features where some minor steam and mainly non-condensable gasses discharge (usually CO_2 but manifestly including H_2S at Mokai). The temperature of mud pools is often well below the boiling point and the heat discharged by mud pools is relatively small (from Prof. Hochstein's Geothermal 603 notes). Warm springs are with temperatures <50°C and natural waters with pH lower than 5.0, as found in geothermal areas such as Mokai, are termed 'acid fluids'.

Why Poor Temperature Gradient?

The Mokai site provided only slight negative correlation for soil temperature tending to decrease further from features (Figure 13), but this is not particularly relevant as origin and characteristics of each feature differed somewhat.

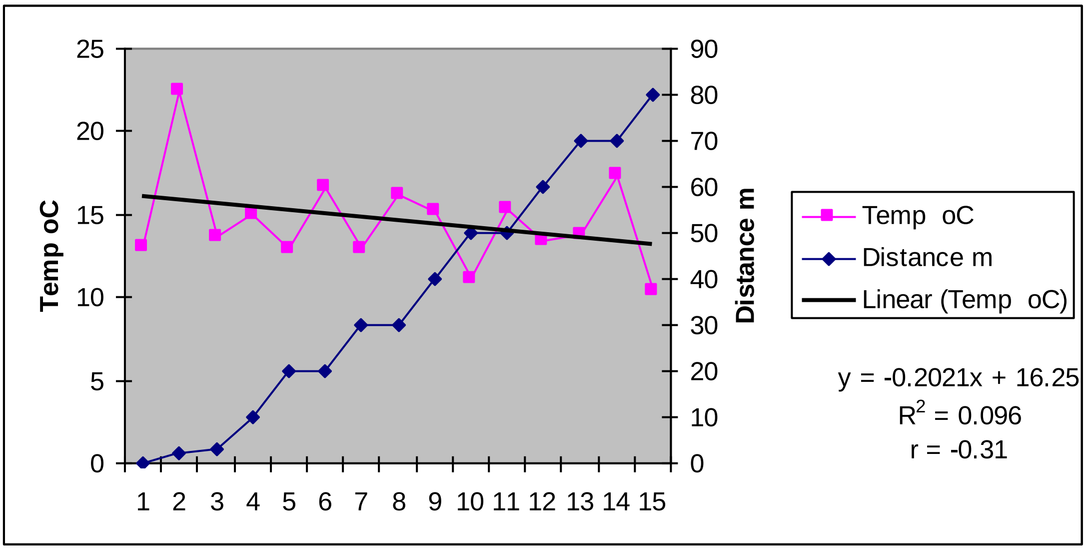

Figure 13. Temperature against Distance for all Transects combined.

There was no assumption that the soil would be heated by radiative conductance, rather the premise was that soils closer would be more influenced by the same factors that concentrated to give rise to the feature. In this case, probably upflow of heated geothermal gasses from depth. Although pasture provided reasonably uniform vegetation cover there were slight topographic variables, dips, hollows and rises, that may have influenced soil temperatures due to subsurface meteoric water flow and cooling. To touch there was a feeling of warmer soil in some samples of Transect C and this was bourn out by some readings, notable the highest (17.4°C) being furthest from the feature at C5. This would be consistent with patchiness of diverse hot spots from rising gasses.

pH and Acidity

Slight negative correlation of soil pH with soil temperature was detected. This would be expected with subsurface heating and acidic alteration as found, indeed, directly adjacent to hot patch, mud pool and acid water features (Figure 14).

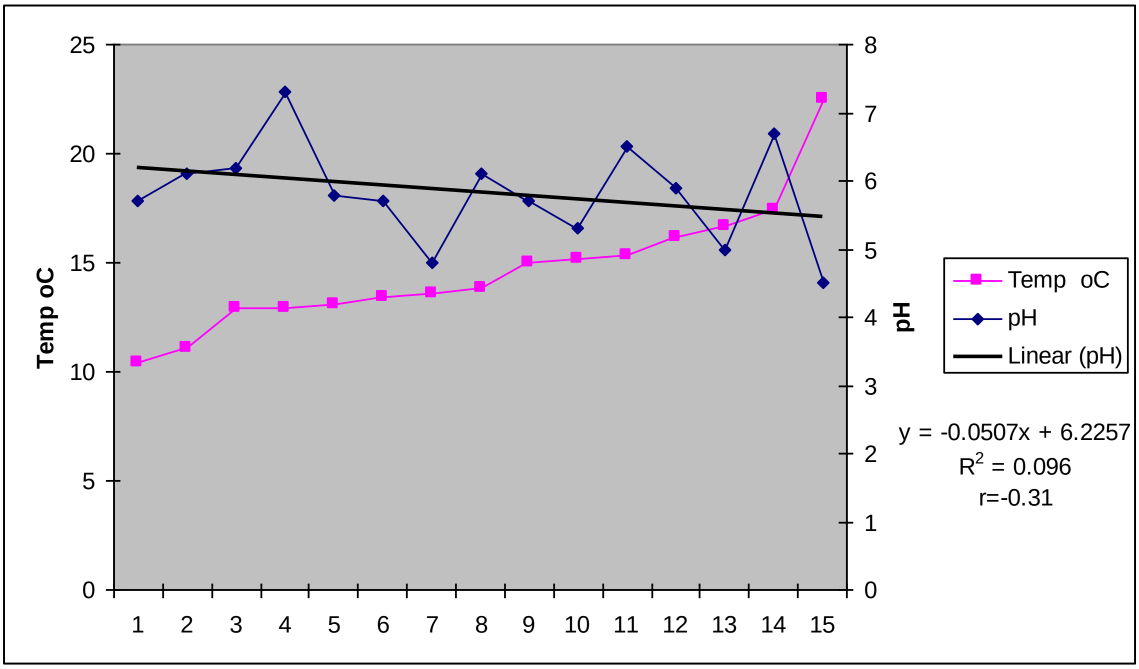

Figure 14. Temperature against pH for all Transects combined.

The study area had a distinct pervading odour of H_2S and the thesis is that convectively heated gasses of geothermal origin percolate through the soil adjacent to active features. Boothroyd (2009) points out that where elemental sulphur forms at ground surface, the air (and soil?) may become more acidic thus influencing biota. Sulphur in its various forms is often toxic, as is CO_2. This is probably the situation prevailing on this site where the ground is bare next to the features - the determining factor is most likely low pH and possibly secondarily the level fluctuation and their intermittent activity [as noted in WRC Monitoring reports of Lynne (2009) and Newson (2010) and as was observed on site when one mud geyser in the large pool erupted to a height of about 5m].

The results showed that pH was particularly low in immediate vicinity of features. However since no clear temperature vs. pH gradient was detected, the pH is deduced to be a consequence of non-condensable gas (NCG) ebullience of deep

source H_2S and CO_2 – the former as indication of sulphates related to SO_2 oxidation to SO4 producing strongly acidic sulphuric acid in H_2SO_4 reactions, and the latter involved in the weakly acidic carbonic acid ($CO_2 + H_2O \rightleftharpoons H_2CO_3$) reactions. A hypothesized and debatable source is that of HCl being produced from superheated steam reaction with feldspars (see conference proceedings - IAEA-TECDOC-1448, 2005 www-pub.iaea.org/MTCD/publications/PDF/te_1448_web.pdf. Accessed Oct., 2011).

Earthworm Population Responses

These preliminary investigations of zonation in soil invertebrates sought particularly well adapted species with characteristics suited to geothermally altered soils. The intimate association of earthworms with their soil medium makes them an obvious monitoring group as well as their being mediators of soil fertility via their activities that aerate, drain, mix and stimulate microbial and other soil biota, positively affecting soil physical and chemical dynamics to the mutual benefit of both plants, the earthworms themselves plus any commensal organisms (Lee, 1985; Sims & Gerard, 1999; Blakemore, 2010a).

Each species has edaphic (i.e., relating to life in the soil) optima of temperature, moisture and pH conducive to survival and reproduction, that they actively seek. Earthworms migrate vertically to avoid environmental extremes but, where soil is heated from below, their strategy of avoidance is probably lateral escape.

Intense habitat selection pressure was exemplified by dead lumbricid earthworms in 100s or 1000s on the bare soil surface at the acid pool embankment at Mokai. These were probably crepuscular or nocturnal wanderers that had become stranded and succumbed to exposure. Whether they were gassed too is unknown. Some were fresh, others aged through desiccation suggesting a sustained occurrence rather than a epoisodic (e.g. response to flooding) event, and a lack of predation was surprising since they are the fundamental key link in all terrestrial food-webs. Possibly, microseismic waves from geothermal activity (detected as deep booming sounds on site) also drives them to the surface in their normal escape response from their ‘race memories’: mistaking the vibrations as mole attacks or for thunder as harbinger of imminent rain and inundation.

Transect analyses showed that earthworms were indeed excluded from soil immediately adjacent to the acidic water features where subsurface temperatures and

pH were most extreme (22.5°C, 4.5) and otherwise tended to respond proportionately to the temperature and especially to the pH of the soil (Figures 15 and 16).

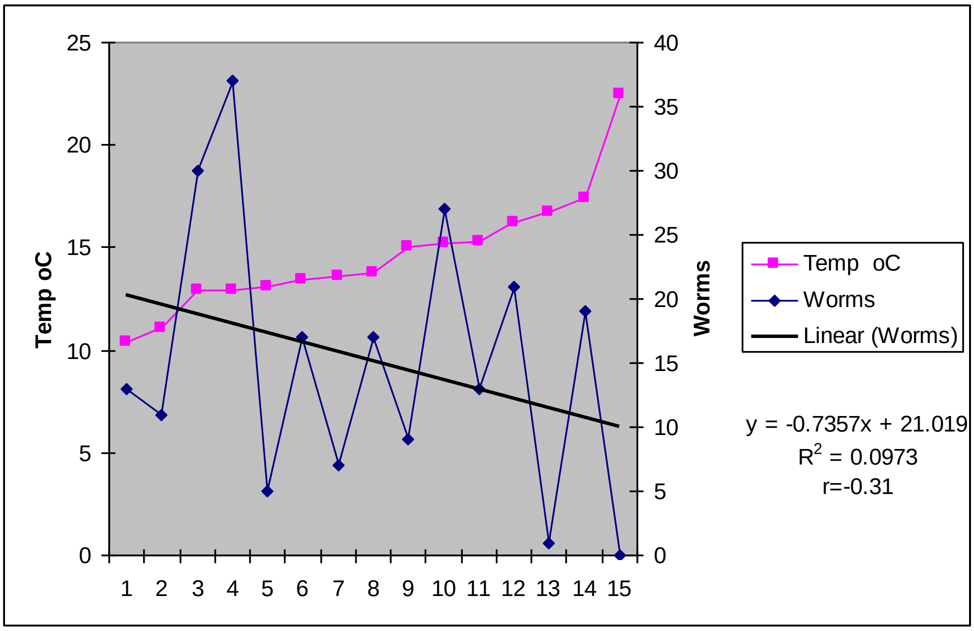

Figure 15. Temperature against Worm counts for all Transects combined.

A slight negative correlation trend was detected between worms and soil temperature gradient (of 10-23°C). Greater sample numbers would possibly have produced less variable data and more conclusive results. [It is yet interesting to note that while the geophysical data has slight standard errors, the bionomic figures have much greater fluctuation range which is characteristic of natural biological/ecological variability].

Strong positive correlation was shown between worms and pH gradient across all transects combined ($p>0.01$). There appears to be a clear relationship between more neutral soils and higher earthworm populations (Figure 16).

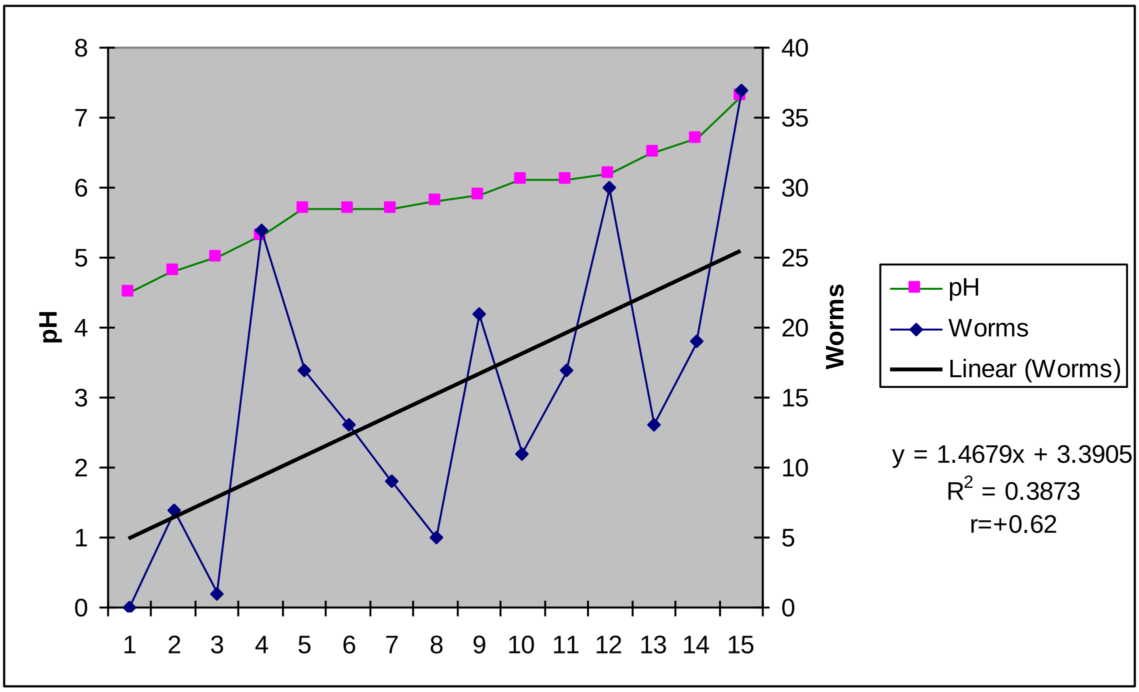

Figure 16. pH against Worm counts for all Transectes combined.

Two possible reasons for the observed positive pH correlation factor are:

1. Worms avoid low pH and/or are attracted to high or neutral pH, as is well reported.
2. High earthworm densities affect the pH of the soil.

The latter is the most probable main contributory cause in the current situation with populations so high that bioturbation alteration effects would be considerable, although behavioural avoidance/selection may have some secondary influence. Passage of soil through a worm's intestine results in its pH shifting towards neutrality in the outcast product (i.e., worm casts). Soil if acidic is rendered more alkaline by additions of calcium carbonate ($CaCO_3$) secretions from their calciferous glands combined with microbial stimulation during gut transit (Lee, 1985; Sims & Gerard, 1999).

This then is the interpretation of results and an extension is that in situations where geothermal alteration does affect temperature and pH, colonization by heat and acid tolerant species may ameliorate the acidification thus making the soil more habitable and the pasture more sustainably productive.

Although pH was not measured at the two locations where *Dendrobaena attemsi* was found (at Golden Springs, Taupo and Auckland), this small species is reported (e.g. Sims & Gerard, 1999) to be acid tolerant in the range pH 3.5-5.6 and to occur in sandy and peaty soils or with mosses. As such it would make a good candidate for colonization of acid soils. This is its first record from near a hot stream.

The conclusion is that, within parameters measured and experimental methods used, the only detected influence was correlation of worms and pH gradient, this partly a product of the worms own self-regulating activity and thus a dependent variable. Further studies could extend soil factors to include Carbon which is indicative of organic matter and C sequestration, as well as measurements of soil moisture and microbial activity.

<u>Earthworm Abundance and Species Biodiversity</u>

An active paddock population gave sample mean count of 17.9 ± s.e. 2.84 (n=12) worms with biomass of approximately 4.0 g ± s.e. 0.62 (n=7) equivalent to 716 m^{-2} (160 g m^{-2}) and extrapolated to a field population of 7.16 million worms ha^{-2} and 1.6 t ha^{-2}. This biomass typically exceeds all other soil fauna combined and matches stocking rates above ground of cattle or sheep.

For the most part only complete worms were counted, and fragments are usually included in the weight once all samples are dried and soil brushed off. Such precise measurements were not practicable under the time and resource constraints here. Note that some workers recommend estimates using oven dry weights but the moisture content and gut contents of a living worm are a valid part of its biomass estimate, no less so than for any other organism, and are more reasonably retained.

Small docile species, such as *Dendrobaena attemsi*, are often missed in hand sorting from dense root mats such as those in the paddock at Mokai. Species delving metres into subsoils, such as *Lumbricus terrestris* Linnaeus, 1758 (called the "night crawler") or *Aporrectodea longa* (Ude, 1885), would also be missed. Complete extraction requires vermifuges such as mustard or wasabi drenches, however abrasive raw pumice below the shallow organic layer in these Mokai soils may preclude deep burrowers.

Regarding the species identified at Mokai, Lee (1959: 354) said "A. caliginosa *is the most common earthworm in New Zealand. It is found throughout the region, in the soils of pasture lands, cultivated lands, exotic forests and plantations, and*

occasionally under native vegetation. Very large populations, up to more than three million per acre (see Waters, 1956, p. 521), are encountered in the soils of high producing pastures." The abundance figure is equivalent to 7.4 million worms per hectare - an extremely high record by World standards. The highest of single samples of 37 worms per 16cm quadrat would represent a population of 1,480 m^{-2} or 14.8 million per hectare, exactly double Waters' figure, however the whole paddock mean is slightly lower at about 7.2 million ha^{-2} which correspond to Waters' (1955) findings.

Mr R. L. Nielson (NZ Dept. Ag.) informed Lee (1959: 353) he found mixtures of what were then called *Allolobophora caliginosa* forma *typica* and *A. caliginosa* forma *trapezoides* in each of twenty localities he examined, with the latter more numerous than the former. The only morphological differences described by Lee (1959: 354) were tubercula pubertatis in *A. trapezoides* morph on 31-33 usually broad and connected by a narrow bridge, rarely forming a continuous ridge and otherwise as for the typical form. No reference was made to differences in size, colour, prostomium nor genital setae that were noted here and as are discussed in detail in Blakemore (2010a).

The summary conclusion, based on information available but contingent on confirmation from DNA samples submitted, is that the species identification of both Mokai morphs is "*Aporrectodea caliginosa* (Savigny, 1826)" with proviso that they differ from morphs found elsewhere and from the 'usual' *A. trapezoides*, thus may either represent NZ domestic ecotypes or indicate the need to investigate resurrection of one or more of the dozen synonyms currently sunk under this binomial epithet. More work is yet required for resolution.

<u>Incidental Survey Results</u>

Incidental survey on the ground unearthed about a dozen earthworm species in total. In the field, two or three Megascolecidae *sensu* Blakemore, 2000c were new *Anisochaeta* and two were new Lumbricidae records. No endemic New Zealand species were found although these are known to be abundant and diverse in native vegetation especially in localities undisturbed by agriculture, industry, or urbanization (e.g. Lee, 1952, 1959; Blakemore, 2010b).

These surveys are cursory and experimental, yet the data provide strong indication of a need for both quantitative and qualitative survey of soil fauna. If obvious earthworms are being overlooked or wrongly identified, then what about the less important soil faunal components such as mites and collembola? That so many new species were located in such short time implies more directed surveys are required, particularly under remnant native vegetation, as are comprehensive tools to correctly identify the species.

An up-to-date interactive computer guide to all NZ's 220 earthworm species is an urgent priority for identification of known natives and for the new tally of overlooked alien/invasive introductions. This needs to be supplemented and corroborated by DNA barcoding of types where possible.

Advice to farmers/pastoralists who desire enhanced earthworm populations at Mokai, as elsewhere, would be, firstly, as caretakers of the land to "*do no harm*" and secondly to encourage natural worm colonization, for example by adding lime to low pH soils or by mulching and supplying organic food that would result in soil conditions most conducive for their optimal survival. Due partly to their incessant activity and natural recycling of organic soil promoting vegetative productivity this also benefits the worms by providing extra food in a closed system and allows sustained grazing by herbivores in a pastoral situation (Blakemore, 2000b).

<u>Other Soil Invertebrates</u>

A few microdrile Enchytraeids, (Oligochaeta : Enchytraeidae), the smaller, ubiquitous in wet soils yet poorly-known relatives of true earthworms, were noted but were not kept for identifications as they have a much lesser contributory role in soil biogenesis and stabilization.

The "Grass grub" scarabs (Coleoptera : Scarabaeidae) anticipated were native *Costelytra zealandica* (White, 1846) but an unknown species was found instead that requires specialist identification (B. Willoughby pers. com.). There are 11 known species in this genus and *C. zealandica* has been called one of the worst pasture pests in New Zealand, causing up to $89M in lost production per year (Garnham & Barlow 1993). However, such statements should be tempered with the current findings that at least some grass grubs co-exist with a healthy earthworm population that may itself be similarly costed to demonstrate a substantial net benefit in pasture production from

the worms' activities that far outweighing slight loss to any particular pest. Encouraging earthworms may emerge as the most cost-effective and natural solution, further over-riding such simplistic pest problem accountancy reckoning if applying broader cost-benefit analyses.

Another thermophilic candidate, if not so rare, would be the Tardigrades (Phylum Tardigrada given vernacular name of water bears of moss piglets) of which NZ has approximately 90 species, that are able to survive extreme environments including temperatures range of close to absolute zero and as high as +151°C (http://en.wikipedia.org/wiki/Tardigrade#cite_note-5). Only one species is yet known from a hot spring, *Thermozodium esakii* Rahm, 1937 from Nagasaki, Japan.

An interesting find on the embankment of the hot pool, near the worm mortuary, was a high density of burrows, some still occupied, of "Devil's coach-horse" beetle larvae. Belonging to family Staphylinidae these Rove Beetles are renowned predators of earthworms, woodlice and carrion. At least one species (*Ocypus olens* formerly *Staphylinus olens* Müller, 1764) has been introduced from Europe to the Americas and Australasia, including New Zealand. Native rove beetles number approximately 800 species (http://www.teara.govt.nz/en/beetles/2) but unfortunately specimens were not kept for positive identification. Its prevalence indicates not only a tolerance for these extreme conditions, but also the presence of sufficient wandering prey to maintain its high population density. A recommendation is to investigate the ecology of this community further, perhaps with pit-fall traps to detect and to monitor movements of its prey, such as the 'humble' earthworm (Figure 17).

Just as geothermal energy seeks its answers underground, so too the environmental aspects of this industry may be served by delving below the surface to reveal the hidden truths and missed diversity literally and immediately beneath our feet. Both engineering and science may thus combine on a common foundation to complete our understanding and to support sustainable life above ground, helping us realize our interconnection to Nature with all its vitality and driving forces.

Figure 17. Photograph of Staphylinid rove beetle (Devil's Coach-horse) adult attacking a distressed mature (clitellate) lumbricid earthworm (from Wikipedia).

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The great effort and delicate liaison at short notice to facilitate this project by Katherine Luketina of Waikato Regional Council is greatly appreciated. Theoretical and intellectual advice was provided by Dr Bruce Willoughby (WRC consultant) plus his hands-on support in the field enriched this study from his repository of knowledge on NZ soils, plants and animals and the ecology that binds them all. Farm manager, Peter Keeling, is thanked for permitting immediate access and the trustees and staff of Tuaropaki who are caretakers of their land are acknowledged, especially Pat Brown,

Gina Rangi, and Anthony the stockman. At Auckland Museum Dr Tom Trnski kindly allowed free use of their facilities for curation and identification of specimens. Dr Bruce Burns, Senior Lecturer in Plant Ecology University of Auckland generously shared what papers and information he had on the subject and gave contact details. These for Ian Boothroyd who although unavailable at this time provided a useful grounding on the topic in his existing publications of environmental surveys, and of John Hutcheson, also uncontactable, who uses flight intercept (malaise) traps recordings in geothermal areas, although these are unlikely to detect many worms.

Direction and enlightenment was professionally provided by the lecturers and staff of the Geothermal Energy course, especially Dr Sadiq Zarrouk, Dr Juliet Newson (who commented positively on a draft report) and Prof. Mike O'Sullivan, plus Emily, Eylem and Tiengang were able assistants.

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APPENDIX I **Raw Statistics**

ns = not significant at probability >10%.

slight indication = probability <~10%.

* = significant at probability, p>0.05 (<5% level).

** = significant at probability, p>0.01 (<1% level).

*** = significant at probability, p>0.001 (<0.1% level).

VassarStats Printable Report 3x3 Factorial ANOVA for Independent Samples standard weighted-means analysis

Mon Oct 31 2011 06:17:10 GMT+0900 (Tokyo Standard Time)

Temp vs. Worms vs. pH			
	TRANSECT A	**TRANSECT B**	**TRANSECT C**
Temp oC	13.1 12.9 12.9 11.1 13.8	13.6 16.7 15.2 13.4 10.4	22.5 15 16.2 15.3 17.4
Worms	5 30 37 11 17	7 1 27 17 13	0 9 21 13 19
pH	5.8 6.2 7.3 6.1 6.1	4.8 5 5.3 5.7 5.7	4.5 5.7 5.9 6.5 6.7

Summary Data		Within each box: Item 1 = N Item 2 = ΣX Item 3 = Mean Item 4 = ΣX^2 Item 5 = Variance Item 6 = Std. Dev. Item 7 = Std. Err.			
	A	**B**	**C**	**C 4**	**Tot.**

Temp	5 63.8 12.76 818.08 1 1 0.45	5 69.3 13.86 982.61 5.53 2.35 1.05	5 86.4 17.28 1530.5400000000002 9.39 3.06 1.37	---	15 219.5 14.6333 3331.23 8.52 2.92 0.75
Worms	5 100 20 2704 176 13.27 5.93	5 65 13 1237 98 9.9 4.43	5 62 12.4 1052 70.8 8.41 3.76	---	15 227 15.1333 4993 111.27 10.55 2.72
pH	5 31.5 6.3 199.78999999999996 0.33 0.58 0.26	5 26.5 5.3 141.11 0.17 0.41 0.18	5 29.3 5.86 174.69 0.75 0.86 0.39	---	15 87.3 5.82 515.59 0.54 0.73 0.19
Tot.	15 195.3 13.02 3721.87 84.22 9.18 2.37	15 160.8 10.72 2360.72 45.5 6.75 1.74	15 177.7 11.8467 2757.23 46.58 6.82 1.76	---	45 533.8 11.8622 8839.82 56.99 7.55 1.13

ANOVA Summary					
Source	**SS**	**df**	**MS**	**F**	**P**
Rows	823.32	2	411.66	10.24	0.0003
Columns	39.68	2	19.84	0.49	0.6167
r x c	196.93	4	49.23	1.22	0.3194
Error	1447.84	36	40.22		

Total	2507.77	44

Critical Values for the Tukey HSD Test			
	HSD[.05]	**HSD[.01]**	Highest Significant Difference=the absolute [unsigned] difference between any two means (row means, column means, or cell means) required for significance at the designated level: HSD[.05] for the .05 level; HSD[.01] for the .01 level. The HSD test between row means can be meaningfully performed only if the row effect is significant; between column means, only if the column effect is significant; and between cell means, only if the interaction effect is significant.
Rows [3]	5.66	7.2	
Columns [3]	5.66	7.2	
Cells [9]	13.25	15.7	

This 3 X 3 ANOVA did not detect significant difference between transects although there was slight indication of interactions between the data (at least for Transect A) which are investigated further.

VassarStats Printable Report 2x3 Factorial ANOVA for Independent Samples standard weighted-means analysis

Mon Oct 31 2011 05:56:44 GMT+0900 (Tokyo Standard Time)

Data Entered			
	Transect A	**Transect B**	**Transect C**
Temperatures oC	13.1 12.9 12.9 11.1 13.8	13.6 16.7 15.2 13.4 10.4	22.5 15 16.2 15.3 17.4
Worm counts	5 30 37 11 17	7 1 27 17 13	0 9 21 13 19

Summary Data	Within each box: Item 1 = N Item 2 = ΣX Item 3 = Mean Item 4 = ΣX^2 Item 5 = Variance Item 6 = Std. Dev. Item 7 = Std. Err.				
	A	**B**	**C**	**C4**	**Tot.**
Temp	5 63.8 12.76 818.08 1 1 0.45	5 69.3 13.86 982.61 5.53 2.35 1.05	5 86.4 17.28 1530.5400000000002 9.39 3.06 1.37	---	15 219.5 14.6333 3331.23 8.52 2.92 0.75
Worms	5 100 20 2704 176 13.27 5.93	5 65 13 1237 98 9.9 4.43	5 62 12.4 1052 70.8 8.41 3.76	---	15 227 15.1333 4993 111.27 10.55 2.72
R3	---	---	---	---	---
R4	---	---	---	---	---
Tot.	10 163.8 16.38 3522.08 93.23 9.66 3.05	10 134.3 13.43 2219.61 46.22 6.8 2.15	10 148.4 14.84 2582.54 42.25 6.5 2.06	---	30 446.5 14.8833 8324.23 57.89 7.61 1.39

ANOVA Summary					
Source	**SS**	**df**	**MS**	**F**	**P**
Rows	1.88	1	1.88	0.03	0.8639
Columns	43.54	2	21.77	0.36	0.7014
r x c	190.55	2	95.28	1.58	0.2267
Error	1442.85	24	60.12		
Total	1678.82	29			

Critical Values for the Tukey HSD Test			
	HSD[.05]	**HSD[.01]**	HSD=the absolute [unsigned]

Rows [2]	5.84	7.92	difference between any two means (row means, column means, or cell means) required for significance at the designated level: HSD[.05] for the .05 level; HSD[.01] for the .01 level. The HSD test between row means can be meaningfully performed only if the row effect is significant; between column means, only if the column effect is significant; and between cell means, only if the interaction effect is significant.
Columns [3]	8.66	11.16	
Cells [6]	15.17	18.67	

Only slight indication of interaction factors were detected between Replicates thus combining data is possible.

VassarStats Printable Report One-Way ANOVA for 3 Independent Samples

Mon Oct 31 2011 05:44:21 GMT+0900 (Tokyo Standard Time)

Values Entered - Soil Temperatures oC

TRANSECT A	TRANSECT B	TRANSECT C		
13.1 12.9 12.9 11.1 13.8	13.6 16.7 15.2 13.4 10.4	22.5 15 16.2 15.3 17.4		

Data Summary

	Samples					
	A	**B**	**C**	**4**	**5**	**Total**
N	5	5	5			15
ΣX	63.8	69.3	86.4			219.5
Mean	12.76	13.86	17.28			14.6333
ΣX^2	818.08	982.61	1530.54			3331.23
Variance	0.998	5.528	9.387			8.5152
Std.Dev.	0.999	2.3512	3.0638			2.9181
Std.Err.	0.4468	1.0515	1.3702			0.7534

ANOVA Summary

Source	SS	df	MS	F	P
Treatment [between groups]	55.5613	2	27.7807	5.24	0.023137
Error	63.652	12	5.3043		
Ss/Bl					
Total	119.2133	14			

Ss/Bl = Subjects or Blocks depending on the design.
Applicable only to correlated-samples ANOVA.

Tukey HSD Test

HSD[.05]=3.89; HSD[.01]=5.2 M1 vs M2 nonsignificant M1 vs M3 P<.05 M2 vs M3 nonsignificant	M1 = mean of Sample A M2 = mean of Sample B M2 = mean of Sample C HSD = the absolute [unsigned] difference between any two sample means required for significance at the designated level. HSD[.05] for the .05 level; HSD[.01] for the .01 level.

Soil temperatures for transects A and C differed significantly (ANOVA greater than 95% probability) thus showed some inter-sample variability. The relationship of either of these to Transect B is likely skewed by rainfall temperature suppression on the previous day when data B was taken. Regardless of this, since A and C were taken on the same day (20th Oct., 2011), then their detected difference may be accepted as indication of some heat source in the soil. That this is due to geothermal source in Transect C is probable as soil here, which tended to yellowy grits, felt warmer to the touch whereas soil in Transect A was notably more uniformly darker, friable, and well-worked by worms.

VassarStats Printable Report One-Way ANOVA for 3 Independent Samples

Mon Oct 31 2011 05:51:34 GMT+0900 (Tokyo Standard Time)

Values Entered - Worm Counts

TRANSECT A	TRANSECT B	TRANSECT C		
5 30 37	7 1 27	0 9 21		

11 17	17 13	13 19

Data Summary

	Samples					
	1	2	3	4	5	Total
N	5	5	5			15
ΣX	100	65	62			227
Mean	20	13	12.4			15.1333
ΣX^2	2704	1237	1052			4993
Variance	176	98	70.8			111.2667
Std.Dev.	13.2665	9.8995	8.4143			10.5483
Std.Err.	5.933	4.4272	3.763			2.7236

ANOVA Summary

Source	SS	df	MS	F	P
Treatment [between groups]	178.5333	2	89.2667	0.78	0.480319
Error	1379.2	12	114.9333		
Ss/Bl					
Total	1557.7333	14			

Ss/Bl = Subjects or Blocks depending on the design.
Applicable only to correlated-samples ANOVA.

Tukey HSD Test

This test will be performed only if K>2 and the analysis of variance yields a significant F-ratio.	M1 = mean of Sample 1 M2 = mean of Sample 2 and so forth.

Little or no evidence against the null hypothesis that samples came from the same population. Variances of means of the earthworm populations in transects were no different than may be obtained by chance (~0.5%). Data from the three transect worm counts may be combined to investigate general trends and abundances. However, if numbers did vary along the transect then this would be overlooked by this statistic and

possibly another test, e.g. Pearsons, is more appropriate for sampling protocols applied.

As a further check on reasonableness to combine data, five sets of Pearson product-moment correlation coefficients, r, were calculated that have maximum values of -1.0 to +1.0 for negative and positive correlation. Its square, R, is Coefficient of Determination - a more direct correlation measure (provided for completeness on graphs).

Tests were performed by manually entering data into Vassar Linear Correlation program (http://faculty.vassar.edu/lowry/corr_stats.html Oct./Nov. 2011).

Firstly, of Transect A, B, C soil temperatures by distance:

Transect A, p= 0.48 ns; Transect B, p= 0.13 ns but slight negative correlation close to 10%; Transect C, p= 0.26 ns but slight positive correlation.

Secondly, of combined data of all Transects for pH by Temperature.

Probability p = 0.4233 thus correlation ns.

Thirdly, of combined data of all Transects for Worms by Temperature:

VassarStats Printable Report Linear correlation and Regression

Mon Oct 31 2011 06:40:35 GMT+0900 (Tokyo Standard Time)

Data Summary

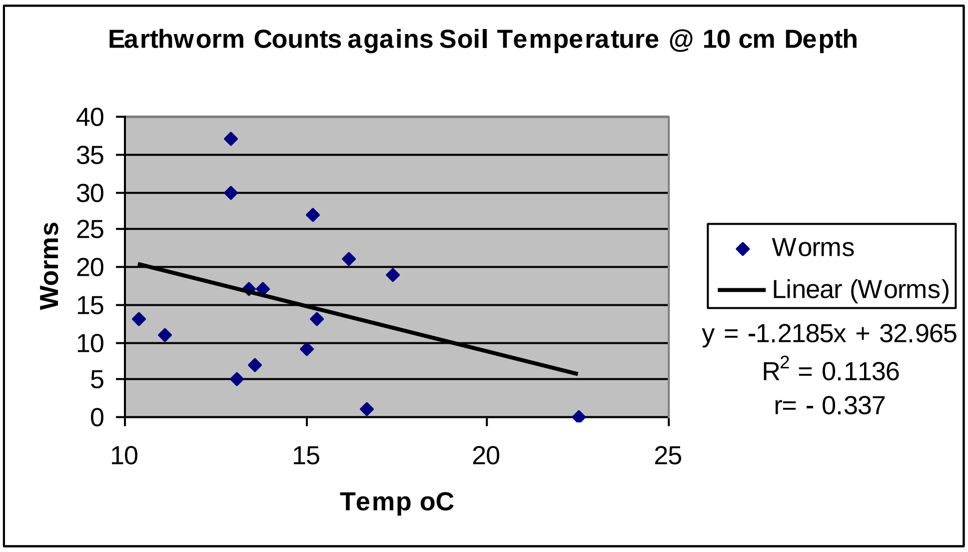
$\Sigma X = 219.5$ $\quad \Sigma X^2 = 3331.23$

$\Sigma Y = 227$ $\quad \Sigma Y^2 = 4993$

$\Sigma XY = 3176.5$

r	r^2	Slope	Y Intercept	Std. Err. of Estimate
-0.337	0.114	-1.219	32.9647	10.3058

t	df	P		
-1.291	13		one-tailed	0.1096
			two-tailed	0.2192



Slight, non-significant, negative trend of random plot of worms by soil temperature. This shows a definite but only significant at >10% trend of negative correlation between soil temperature and worm counts (p=0.1096; r=-0.337; n=15); the worms tended to decline where temperatures were hottest.

A separate Correlation tests on Transect A data alone showed p = 0.1193 (i.e., >10%) and r=-0.418 thus it is only a slightly more defined trend than for combined data.

Fourthly, of combined data of all Transects for Worms by pH:

VassarStats Printable Report Linear correlation and Regression
Mon Oct 31 2011 06:45:12 GMT+0900 (Tokyo Standard Time)

Data Summary

$\Sigma X = 87.3$ $\Sigma X^2 = 515.59$

$\Sigma Y = 227$ $\Sigma Y^2 = 4993$

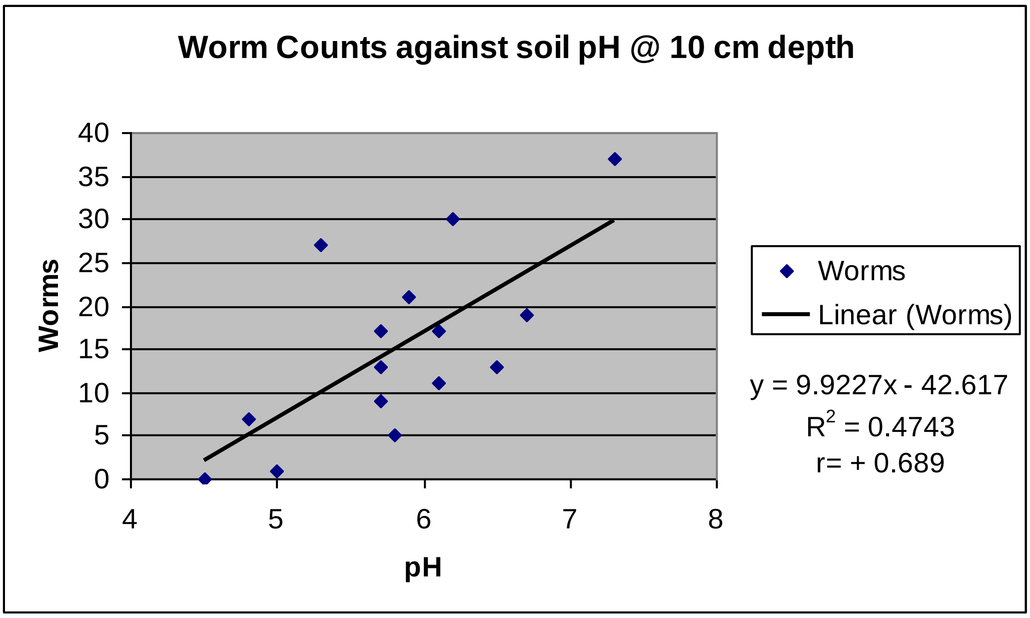
$\Sigma XY = 1395.6$

r	r^2	Slope	Y Intercept	Std. Err. of Estimate
0.689	0.474	9.923	-42.6168	7.9367

t	df	P		
3.425	13		one-tailed	0.0023
			two-tailed	0.0045

0.95 and 0.99 Confidence Intervals of rho

	Lower Limit	Upper Limit
0.95	0.274	0.887
0.99	0.103	0.92



This shows a strong probability (>99%) of positive correlation between pH and worm counts for all samples combined (p=0.002; r=0.689;n=15).

Finally, of partial combined data for Worms by Biomass (g).

Probability p = 0.0275 (p=97%) thus good correlation, as would reasonably be expected, but due to probable inaccuracies of these data, they are not presented in detail.

These results are represented graphically in Excel charts presented in the Discussion.

APPENDIX II - Topography, temperature and soil description and pasture composition courtesy of Dr Bruce Willoughby.

Soil fauna survey – geothermal effects
Notes prepared by B. Willoughby September 2011

Survey site: Tuaropaki Station Mokai

Thompson (1965) recorded an average temperature in September in soil at a depth of 1.00m of 10.5^{0}C in the region. Temperature variations were considerable and attributed to geothermal activity. There was no correlation with topography.

The paddock topography was for the most part flat to gently rolling. The soil was a yellow brown loam, ash derived and based on a little weathered coarse alluvial sorted pumice. The dark coloured organic layer extended [to] 100mm – 150mm. Subsoil extended from 150mm to untested depth.

Pasture composition (Table1) was relatively uniform across the sample area and the paddock at the time of sampling was being grazed by approximately 70 dairy heifers. Much of the area sampled constituted a stock camp with attendant heavy cover of stock faeces (estimated 5% cover by area).

Table 1: Predominant grass, legume and weed species present in sample paddock in September 2011.

Common name	***Generic name***	**% cover**
Grasses	**Total**	**40**
Browntop	*Agrostis tenuis*	20
Poa	*Poa annua*	10
Perennial ryegrass	*Lolium perenne*	5
Yorkshire fog	*Holcus lanatus*	5
Legumes	**Total**	**10**
White clover	*Trifolium repens*	10
Lotus	*Lotus pedunculatus*	Tr
Weeds	**Total**	**50**
Sorrel	*Rumex acetosa*	
Chickweed	*Cerastium fontanum*	
Daisy	*Bellis* sp.	
Nodding thistle	*Cardus nutans*	
Dock	*Rumex* sp.	

References

Thompson, G.E.K. 1965 *Regional ground temperature survey in the Taupo – Reporoa depression New Zealand* Journal of Geology and Geophysics. 8:527-29.